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Inter-row hoeing for weed control in organic spring cereals—Influence of inter-row spacing and nitrogen rate

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ABSTRACT

Inter-row hoeing has become increasingly important for weed control in organic spring cereals since the introduction of automatic steering systems. The technology requires a widening of current inter-row spacing for spring cereals in order to provide sufficient room for accurate operation of a hoe share between crop rows. However, there is considerable uncertainty about the optimal combination of inter-row hoeing, inter-row spacing and nitrogen (N) rate in terms of weeding effectiveness and crop yield. The aim of this study was to investigate the effect on weed and crop growth of the interaction between five inter-row spacings (125, 150, 200, 250, and 300 mm) and two N rates (50 and 100 kg NH_4-N ha^{-1}). Three field experiments were conducted in spring barley and two in spring wheat. One hoeing pass was applied for each inter-row spacing using a share width that worked 15–47 mm from the crop row. The immediate effect on weed numbers following hoeing was a 80–90% reduction in barley and a 63–80% reduction in wheat, but with no significant differences between spacings and N rates. However, the effect on weed biomass at crop anthesis was minor in barley because the crop itself substantially suppressed weed growth. Spring wheat was less competitive and inter-row hoeing reduced weed biomass by 60–70% compared to the standard 125 mm spacing without hoeing. The widening of inter-row spacing appeared not to reduce crop yield or grain quality. Prerequisites for successful inter-row hoeing in spring cereals include retained crop stands when increasing inter-row spacing and the avoidance of crop injuries from inaccurate steering.

1. Introduction

Weed harrowing is the principal physical weed control method applied in spring cereals. It is a full-width treatment affecting both the crop and weeds, usually employing one to three passes depending on the extent of the weed problem. Its weeding mechanisms and adjustments for optimal use are explained in Kurstjens and Kropff (2001) and Rasmussen et al. (2010) for example. The adoption of weed harrowing in practice has been difficult in many cases and there seems to be a steady move away from this technology towards other solutions. Optimal timing, settings and execution are the main challenges of weed harrowing mentioned by practitioners, which in many cases has resulted in poor weed control and occasionally significant crop yield loss. Erect dicotyledonous weed species with taproots and tall-growing grasses are particularly difficult annual weeds to control, and perennial weed species are not greatly affected (Rasmussen, 1998). Species such as *Sinapis arvensis* L., *Brassica rapa* L. and *Raphanus raphanistrum* L. are particular troublesome because they establish quickly, have fast initial growth rates and can emerge in series of cohorts. Weed harrowing needs to target very small, cotyledon-staged weeds, and repeated treatments with short intervals are necessary at times for satisfactory control (Rasmussen et al., 2010).

Inter-row cultivation with steerage hoes is widely applied in typical row crops where operation between crop rows is straightforward. The weeding device is usually a goosefoot share, providing a cutting action that can almost completely remove inter-row weeds unless soil conditions are wet or weeds have become too large to be controlled (Melander et al., 2005). Inter-row hoeing may also be used in cereals

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Table 1
Experimental details showing the crops and the years in which they were grown. The factors N input, inter-row spacing ± inter-row hoeing and key assessments were conducted in all crops and years. Abbreviations for N input and hoeing treatments are shown in parentheses.

Crops and years	NH_4-N kg ha^{-1}	Inter-row spacing (mm) ± inter-row hoeing	Key assessments
Spring barley (2014, 2015, 2016) and spring wheat (2015, 2016)	50 (50N) 100 (100N)	125 non-hoed (125NH) 125 hoed (125H), 70 mm SW[a], - 55 mm 'untreated' area[b] 150 hoed (150H), 120 mm SW[a], - 30 mm 'untreated' area[b] 200 hoed (200H), 170 mm SW[a], - 30 mm 'untreated' area except in 2014 with 80 mm 'untreated' area[b] 250 hoed (250H), 220 mm SW[a], - 30 mm 'untreated' area except in 2014 with 45 mm 'untreated' area[b] 300 hoed (300H), 250 mm SW[a], -50 mm 'untreated' area except in 2014 with 95 mm 'untreated' area[b]	1. Crop plants counted at the one-leaf stage (all plots) 2. Weed counts 2 days before hoeing (all plots except 125NH) 3. Weed counts 8–10 days after hoeing (all plots) 4. Weed and crop biomass sampling at crop anthesis in late June (all plots) 5. Crop tiller counts 4–6 days before crop harvest (all plots) 6. Crop harvest mid-August (barley) and late August (wheat) (all plots)

[a] SW = share width. In 2014, SW was 120 mm for 200-mm inter-row spacing and 205 mm for both 250 and 300-mm inter-row spacing.
[b] 'Untreated' area is the inter-row space not directly impacted by the share width.

grown with increased inter-row spacings to make room for the operation of a goosefoot share between crop rows (Jabran et al., 2017). Its principal application is against annual weeds, but it can have some effect against perennials as well (Graglia et al., 2006). It will not eradicate a perennial weed problem since belowground propagules are not directly affected. However, shoot removal will stimulate re-sprouting, which depletes the belowground food reserves. At the same time, translocation of photosynthetic assimilates to roots and rhizomes is interrupted, and overall these effects can impede the regenerative capacity of perennial weeds (Graglia et al., 2006).

Inter-row hoeing for weed control in cereals and other crops grown with narrow inter-row spacing has been the subject of renewed interest in recent years thanks to camera-based automatic steering systems. Vision technology eases the steering task and enables inter-row hoeing with a higher operational capacity as implement width and driving speed can be increased (Jabran et al., 2017). Previous studies on inter-row hoeing in conventionally grown cereals have shown greater effectiveness against problematic weed species such as grasses and tap-rooted species that have an erect growth habit (Melander et al., 2003). Timing of treatment was less crucial with inter-row hoeing than weed harrowing because the cutting action of the shares also controls weeds with more than two or three true leaves. However, weeds growing in the crop rows (intra-row weeds) are not directly impacted by the hoe shares and thus are not controlled unless sideways soil movement causes some soil coverage of the intra-row weeds. Another drawback is a yield penalty of 11–12% associated with the widening of inter-row spacing from the standard 125 mm to 240 mm (Melander et al., 2003).

Kolb et al. (2010) achieved improved weed control, yields and profitability using inter-row hoeing in organic spring barley with high infestations of white mustard (*Sinapis alba* L.) in contrast to merely improving crop competition through higher seed rates and spatial arrangement of crop plants. However, inter-row hoeing did not achieve better results at a lower weed infestation level. The study compared just one widened inter-row spacing with the standard spacing (177 mm *versus* 228 mm). There is considerable uncertainty about the optimal combination of inter-row spacing and inter-row hoeing to maximise weed suppression and crop yield. Crop yield and weed control are to some extent inversely related. Wide inter-row spacing means a greater proportion of the surface area can be hoed, which should improve weed control and thus crop yield, but a widening of the inter-space beyond the limits for effective utilisation of the resources can counteract the benefits of weed control, as seen with conventional cereals (Melander et al., 2003). However, moderate widening of the inter-row spacing does not appear to reduce yields of cereals in organic farming that are fertilised with solid or liquid manures, where much of the nitrogen (N) is in organic form and released more slowly (Hiltbrunner et al., 2005). In Danish organic agriculture, NH_4-N rates from slurry applied for spring cereals are typically 100 kg ha^{-1} on dairy farms and around 50 kg ha^{-1} on arable farms without livestock (Bertelsen 2015; personal communication). There has not yet been a thorough investigation of the effect on weed growth and crop yield of interactions between N fertilisation rates and inter-row hoeing at different inter-row spacings.

The objective of this study was therefore to investigate the interaction between inter-row hoeing at different inter-row spacings and N rates in terms of their impact on weed growth and crop yield in organic spring cereals. It was hypothesised that:

- increasing the inter-row space results in greater weed control from inter-row hoeing than smaller spacing
- increasing the N input (50 kg *versus* 100 kg NH_4-N ha^{-1} in animal manure) improves crop growth relative to weed growth from weeds surviving inter-row hoeing
- weed control effects are greater in spring barley than in spring wheat because barley suppresses weeds surviving inter-row hoeing more effectively
- crop yield and quality are unaffected by inter-row spacing in organic farming

2. Materials and methods

2.1. Experimental layout and treatments

In total five experiments were conducted on a sandy loam soil at the Flakkebjerg Research Centre (55°19'N, 11°23'E), Denmark. The factors inter-row spacing with inter-row hoeing and N input were investigated in terms of their impact on crop and weed growth in spring barley (*Hordeum vulgare* L.) and spring wheat (*Triticum aestivum* L.) in organic farming. Table S1 in Supplementary shows the mean temperatures and rainfall during the main growing season (April–July) for each month and year, while Table 1 gives an overview of the crops and years in which they were grown and the experimental factors studied for each combination of crop and year. Spring barley was sown on 2 May 2014, 9 April 2015 and 20 April 2016 using the two-row variety *Evergreen*. Spring wheat, variety *Bittern*, was sown on the same dates as barley in 2015 and 2016. Seed rates were adjusted to target approximately 400 plants m^{-2} for both crops and obtain the same plant density m^{-2} irrespective of inter-row spacing. To achieve this, the seed rate per metre of row was proportionally increased with widening inter-row spacing. The spring cereals were grown according to Danish organic standards. Nutrients were applied as anaerobically-digested slurry at rates providing 50 kg NH_4-N ha^{-1} (87 kg total N, 14 kg phosphorous, 33 kg potassium ha^{-1}) and 100 kg NH_4-N ha^{-1} (174 kg total N, 28 kg phosphorous, 65 kg potassium ha^{-1}). The slurry was injected to 5–8 cm soil depth shortly before final seedbed preparation and sowing.

Slurry application and inter-row hoeing (treatments 125NH-300H, Table 1) were arranged in a randomised split-plot design with N rate as the main plot and inter-row hoeing as sub-plots, all replicated in four complete blocks. In total 48 plots (2 N-levels × 6 inter-row hoeing × 4 blocks) were included for each combination of crop and year. Gross plot size was 2.5 m × 15 m and net plot size was 1.5 m × 10 m, with each plot separated by 2.5-m wide safeguards at the ends. Inter-row hoeing was conducted when spring wheat was at growth stage 14–21 and spring barley at stage 21–22 according to the BBCH scale developed from Zadoks et al. (1974). Only one pass was made in each experiment using 'goosefoot'-shaped shares, with the widths shown in Table 1. Each share cultivated one inter-row space at 2–3 cm soil depth at a low forward speed of 1.5–2.0 km h^{-1} under manual steering to avoid crop injuries from steering errors or excessive soil coverage of crop plants. It was not the aim to reflect driving speeds that are relevant for practice. The majority of weeds had typically developed two to four true leaves at the time of hoeing.

2.2. Data recording

Crop establishment was recorded by counting the number of emerged crop plants at the one-to-two true leaf stage in 6 × 1 m row lengths randomly selected in each plot. Weeds were counted one to two days before inter-row hoeing and again eight to ten days after hoeing. The counts were made for intra-row weeds, defined as those growing in the crop line and 25 mm on each side of the crop line, and for inter-row weeds, defined as those growing in the remaining area. Six quadrats, each 100 cm × 5 cm, were placed randomly in the intra-row area and six quadrats in the inter-row area using a 100 × 5 cm quadrat for 125 mm inter-row spacing and a 100 × 10 cm quadrat for 150–300 mm inter-row spacing. All the quadrats were placed with the long side in the longitudinal direction of the rows. The weeds were counted species-wise for the three to five principal species and the remainder as one group. The principal weed flora in all years consisted of *S. arvensis*, *Chenopodium album* L., *Capsella bursa-pastoris* (L.) Medik., *Bilderdykia convolvulus* (L.) Dumort and *Polygonum aviculare* L. Crop and weed biomasses were recorded when the crops had reached anthesis (BBCH 65-69), typically in late June or early July. Four metres of crop row were cut at ground level in all plots and the plant material separated into crops and weeds. Weed biomass in the inter-row area was harvested by cutting all weeds at ground level in four quadrats (100 cm × 10 cm for 150–300 mm inter-row spacing and 100 × 5 cm for 125 mm inter-row spacing) per plot. The crop and weed fractions were oven-dried for 24 h at 80 °C to obtain dry matter content (DM).

Intra-row and inter-row weed density and biomass were calculated as the density or biomass m^{-2} of the specific inter-row treatment. For example one m^2 (1 m × 1 m) of 200 mm inter-row spacing has 5 rows and 5 inter-row spacings corresponding to an intra-row area of 0.25 m^2 (5 × 0.05 m) and an inter-row area of 0.75 m^2 (5 × 0.15 m). The sum of the two areas gave the total weed density m^{-2} or biomass m^{-2}.

Four to six days before crop harvest, four metres of crop row were cut at ground level in all plots and the number of ears (productive tillers) counted. Each plot was combined for grain yield on 14 August 2014 (barley), 20 August 2015 (barley), 28 August 2015 (wheat), 17 August 2016 (barley) and 25 August 2016 (wheat). Dry matter and protein content of the grain were determined using a near-infrared spectroscopy analyser (Infratec™ 1241 Grain Analyzer, Foss A/S; Buchmann et al., 2001). Grain yields were adjusted to 85% dry matter content. Thousand kernel weight (TKW) was obtained by weighing three samples of 100 kernels from each plot.

2.3. Data analyses

Weed and crop growth were analysed using a generalised linear mixed model with normally distributed data (McCullagh and Nelder, 1989). However, in several cases variance homogeneity was only achieved following transformation. The appropriateness of transformation was visually assessed by the distribution of residuals, and the assumption of normality after transformation was analysed using PROC UNIVARIATE in SAS (SAS Institute Inc., 2010). There were no indications of other distributions being more appropriate than the normal distribution. The procedure PROC CORR and SPEARMAN correlations matrix in SAS were used to test for correlations between independent variables in the mixed models. Subsequently, collinearity diagnoses were performed with PROC REG and the options TOL, VIF and COLLIN to check for multicollinearity among independent variables. The diagnoses showed no sign of collinearity in any case.

The immediate effect of inter-row hoeing based on the weed counts performed one to two days before hoeing and eight to ten days after hoeing was calculated as the rate *r* of change in numbers of weeds in total and *S. arvensis* in particular,

$$r = \ln\left(\frac{N_{d+10}}{N_d}\right), \tag{1}$$

where N_d is the weed number shortly before hoeing and N_{d+10} is the weed number approximately 10 days after hoeing.

All analyses on weed and crop responses were made in two stages. In stage (I), the plain and general effects of the categorical variables crop (barley, wheat), N input (50N, 100N) and treatments (125NH–300H) were estimated across years. For that purpose, fixed effects of full models included crop, N input and treatments. The random terms were year (2014 (only barley), 2015, 2016), block within year and crop and the interaction between N input and block within year and crop to account for the experimental design. However, factors studied in field experiments usually interact with growing season and to scrutinize these interactions, a stage (II) analysis was also made. Year was included as a fixed effect along with the other fixed effects mentioned above. The random terms were then block within year and crop and the interaction between N input and block within year and crop. In the analysis of the immediate effects, the covariate N_d described a general linear relationship between *r* and N_d, to adjust for differences in the weed population before hoeing.

Parameters were estimated using residual likelihood estimations. Calculations were performed using the MIXED procedure of SAS (SAS release 9.2), and means were calculated as least square means (LSM). Models were reduced by excluding non-significant effects based on likelihood ratio tests and Akaike's information criterion (Akaike, 1974). The denominator degrees of freedom (DDF) in *F*-tests and *t*-tests for mean separations were calculated according to Kenward and Roger (1997). The option CONTRAST was used to test groupings of treatments. Probability values for multiple mean separations were adjusted according to the Tukey-Kramer method.

The outcomes of the stage (I) analyses are mainly explained in the main text except for Table 4. However, the same data are shown year-wise under the stage (II) analyses.

3. Results

3.1. Crop and weed growth

Crop plant density in the crop rows increased proportionally with wider inter-row spacings where target crop plant densities were roughly met (Table S2). However, the target of having approximately the same crop plant density per m^2 for all inter-row spacing was not fully achieved in 2014 and 2015 (Table S2). In 2014, the lower crop plant density for 200H, 250H and 300H was mainly due to a technical

Table 2
Weed pressure in spring wheat and spring barley in 2014–2016. Numbers of weeds in total and of *Sinapis arvensis* before inter-row cultivation are shown as means of all hoeing-treatments and N-levels. Weed and crop biomasses at crop anthesis are shown for both N-levels at 125NH. Standard errors of means in parentheses.

Year	Crop	Weed number in total (no. m^{-2})	*Sinapis arvensis* (no. m^{-2})	Weed biomass (g DM m^{-2})		Crop biomass (g DM m^{-2})	
				50N	100N	50N	100N
2014	Barley	200 (11.7)	13 (3.2)	31 (8.7)	23 (8.7)	504 (20.6)	574 (24.0)
2015	Barley	296 (12.2)	9 (1.1)	22 (1.8)	15 (4.7)	795 (59.5)	1047 (126.6)
	Wheat	343 (15.2)	18 (2.6)	65 (25.5)	61 (11.4)	764 (110.5)	991 (34.7)
2016	Barley	330 (23.1)	21 (4.1)	9 (2.7)	23 (9.2)	691 (59.7)	714 (51.9)
	Wheat	366 (15.9)	22 (3.6)	38 (4.0)	64 (12.3)	528 (8.2)	579 (21.3)

problem where individual seeding tubes did not provide enough seeds per row. In 2015, however, crows fed on the rows shortly after sowing, with a strong preference for 200H and 250H, and predominantly in spring wheat. Nevertheless, these losses of crop plants can be used to acquire an understanding of important principles about inter-row hoeing for weed control in spring cereals. The number of productive tillers per m^2 and per crop plant that established in spring was strongly affected by year ($P < 0.0001$ for both variables) and crop ($P < 0.0001$ for both variables). The greatest tillers m^{-2} and plant^{-1} were produced in 2015, with spring barley yielding the most tillers (both m^{-2} and plant^{-1}) in both years (Table S3). Treatment 100N generally increased tiller production as compared to 50N in barley ($P < 0.0001$ for both variables), whereas the positive effect was slight and insignificant for wheat. Increasing inter-row spacing generally had a minor influence on tiller production, except when crop plant number became very low in spring wheat in 2015.

Weed density before inter-row hoeing was moderate in all three seasons for organic growing conditions (Table 2). Weed biomass for 125NH was generally higher in spring wheat than in spring barley. The proportion of weed biomass relative to crop biomass in 125NH ranged from 1 to 6% in barley and from 6 to 11% in wheat.

3.2. Immediate effects on weed numbers

3.2.1. Stage (I) analysis

Weed control effects for all weed species in total were generally 10% lower in spring wheat than in spring barley, 76% *versus* 86% ($P < 0.0001$). Nitrogen level had no effect and crop did not interact with inter-row spacing. In general for both crops, 300H controlled more weeds than the other four spacings (86% *versus* 80%, $P < 0.0001$). Weed control effects against *S. arvensis* in particular tended to be greater in spring barley than in spring wheat (67% *versus* 57%, $P = 0.0799$).

3.2.2. Stage (II) analysis

Total weed density showed significant main effects of crop ($P < 0.0001$), year ($P = 0.0389$) and inter-row spacing ($P = 0.0002$) and a significant interaction between inter-row spacing and year ($P < 0.0001$). The weed control effects of hoeing are presented in Table 3, which shows that the effects in spring barley were consistent across years and greater than in spring wheat except for 300H in wheat in 2016. The number of *S. arvensis* plants in particular, was reduced at the same rate across years with no significant influence of N input or crop (Table 3).

Table 3
Effects on number of weeds species in total and *Sinapis arvensis* in particular following inter-row hoeing 125H–300H in 2014–2016 (stage (II) analysis). Effects are shown as least square means (LSM) of rates *r* of weed population change from before and after hoeing (Eq. (1)) and as % weed reduction. The probability of $r \neq 0$ denotes the significance of population change. Maximum standard errors of differences (SED) between *r*-LSMs are shown in italics. Different letters alongside *r*-LSMs in columns indicate significant differences at $P \leq 0.05$ (Tukey–Kramer test).

Crop	Species	Year	Inter-row spacing (mm)	Population change rate *r*	Probt. $r \neq 0$	% weed reduction
Spring barley	Total	2014–16	125H	−1.86[ab]	< 0.0001	84.5
			150H	−1.71[a]	< 0.0001	81.9
			200H	−1.85[a]	< 0.0001	84.3
			250H	−1.94[ab]	< 0.0001	85.6
			300H	−2.27 [b]	< 0.0001	89.7
			SED	*0.151*		
	Sinapis arvensis	2014–16	125H	−1.34[a]	0.0018	73.8
			150H	−1.00[a]	0.0084	63.1
			200H	−1.60[a]	0.0006	79.8
			250H	−1.11[a]	0.0048	67.1
			300H	−1.35[a]	0.0017	74.1
			SED	*0.302*		
Spring wheat	Total	2015	125H	−1.60[a]	< 0.0001	79.8
			150H	−1.32[a]	< 0.0001	73.2
			200H	−1.57[a]	< 0.0001	79.1
			250H	−1.24[a]	< 0.0001	71.2
			300H	−1.00[a]	< 0.0001	63.3
			SED	*0.194*		
		2016	125H	−1.29[a]	< 0.0001	72.4
			150H	−1.37[a]	< 0.0001	74.6
			200H	−1.25[a]	< 0.0001	71.2
			250H	−1.30[a]	< 0.0001	72.8
			300H	−2.34[b]	< 0.0001	90.4
			SED	*0.199*		
	Sinapis arvensis	2015–16	125H	−1.16[a]	0.0006	68.7
			150H	−0.47[a]	0.1512	37.5
			200H	−0.84[a]	0.0120	56.6
			250H	−0.92[a]	0.0057	60.1
			300H	−1.13[a]	0.0008	67.6
			SED	*0.460*		

3.3. Weed and crop biomasses

3.3.1. Stage (I) analysis

Four times more weed biomass in total was in general harvested in spring wheat (32 g m^{-2}) at anthesis than in spring barley (8 g m^{-2}) ($P < 0.0001$), both figures averaged over all treatments. Again N level did not affect weed biomass dynamics but inter-row spacing interacted with crop ($P = 0.0470$). Treatments 125H–300H were not significantly different in spring barley but they all differed significantly from 125NH and in general these treatments reduced weed biomass by 61% ($P < 0.0001$). Weed biomass reduction in spring wheat following inter-row hoeing was only 39% when contrasting 125NH with 125H–300H ($P = 0.0234$). Differences between 125H–300H were minor in spring wheat.

Spring barley produced 13% more crop biomass at anthesis than spring wheat ($P = 0.0013$), and 100N increased crop biomass by 18% in both crops ($P < 0.0001$) (data not shown).

3.3.2. Stage (II) analysis

Treatment effects on weed and crop biomasses at anthesis are

Table 4
Stage (I) analyses showing least square means (LSMs) of grain yields, protein contents and thousand kernel weights (TKW) for the main effects of inter-row spacing for each crop. Different letters alongside LSMs in rows within crop indicate significant differences at $P \leq 0.05$ (Tukey–Kramer test). SED is maximum standard errors of differences between means.

Crop	Years	NH_4-N kg ha^{-1}	Inter-row spacing (mm)						SED
			125NH	125H	150H	200H	250H	300H	
			Grain yield (t ha^{-1})						
Barley	2014–16	50, 100	5.41^{a}	5.07^{ab}	4.68^{c}	4.22^{d}	4.72^{bc}	4.77^{bc}	*0.121*
Wheat	2015–16	50, 100	4.60^{ab}	4.70^{a}	4.57^{ab}	4.16^{b}	4.04^{b}	4.53^{ab}	*0.182*
			Protein content (%)						
Barley	2014–16	50, 100	10.5^{a}	10.5^{a}	10.6^{a}	10.8^{a}	10.6^{a}	10.9^{a}	*0.15*
Wheat	2015–16	50, 100	11.0^{a}	11.5^{bc}	11.2^{ab}	11.4^{abc}	11.7^{c}	11.5^{bc}	*0.13*
			TKW (g)						
Barley	2014–16	50, 100	45.9^{a}	46.3^{ab}	46.0^{a}	46.8^{ab}	47.5^{b}	46.7^{ab}	*0.46*
Wheat	2015–16	50, 100	46.4^{a}	45.8^{a}	46.1^{a}	47.2^{a}	47.0^{a}	46.7^{a}	*0.49*

analysed year and crop-wise due to strong 3-way and 4-way interactions with year and crop. In the dry season of 2014 (June and July in Table S1), N input had no effect on weed biomass and there was no difference in 125H–300H; on average inter-row hoeing reduced weed biomass by 74% ($P < 0.0001$) as compared to 125NH.

In seasons 2015 and 2016, total weed biomass in spring barley was not affected either by inter-row hoeing or by N-level (Figs. 1 and 2). Spring wheat was generally weedier than spring barley in both years ($P < 0.0001$ for both years), but again N-level did not explain any of the variation for total, intra-row and inter-row weed biomasses in spring wheat. The loss of crop plants in spring wheat in 2015 (Table S2) reduced the crop's competitive ability (Fig. 3). Treatments 125H and 150H reduced total weed biomasses by 63% on average in 2015 as compared to 125NH. In 2016, only 300H significantly reduced weed biomass by 71% in wheat in comparison with 125NH. The effects were mainly caused by a reduction of intra-row weed biomass (Fig. 2).

Spring barley biomass at anthesis in 2014 did not respond to N input

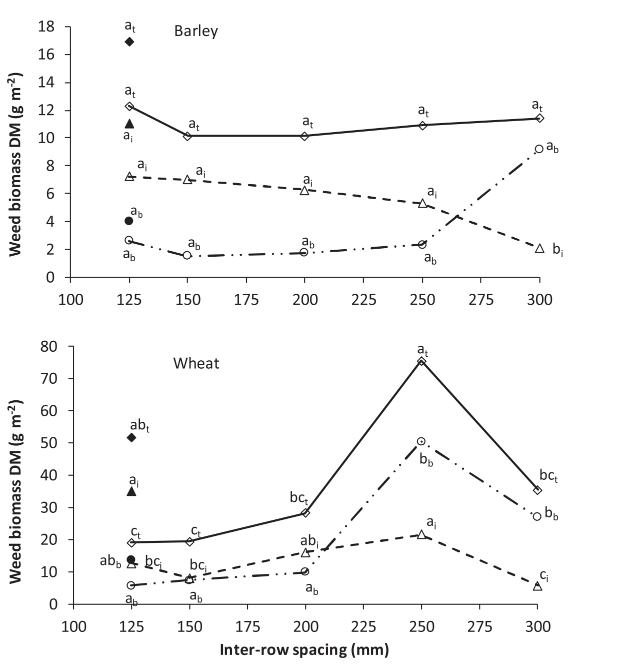

Fig. 1. Total, intra-row and inter-row weed biomasses related to inter-row spacing (125H–300H) in spring barley and spring wheat in 2015. Treatment 125NH is also shown. Observed values are backtransformed means from log-transformation. Means with similar letters within crop and weed biomass category are not significantly different (Tukey–Kramer test). Lower case $_t$ = total biomass, $_i$ = intra-row biomass, $_b$ = inter-row biomass.

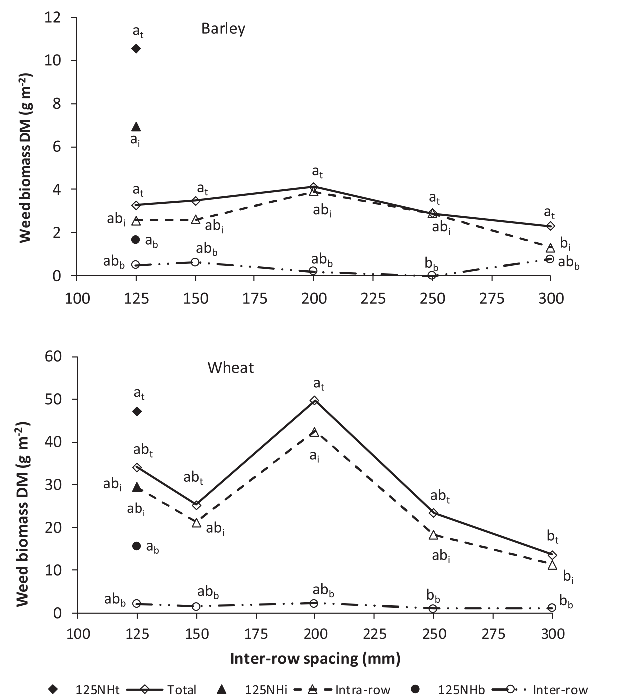

Fig. 2. Total, intra-row and inter-row weed biomasses related to inter-row spacing (125H–300H) in spring barley and spring wheat in 2016. Treatment 125NH is also shown. Observed values are backtransformed means from log-transformation. Means with similar letters within crop and weed biomass category are not significantly different (Tukey–Kramer test). Lower case $_t$ = total biomass, $_i$ = intra-row biomass, $_b$ = inter-row biomass.

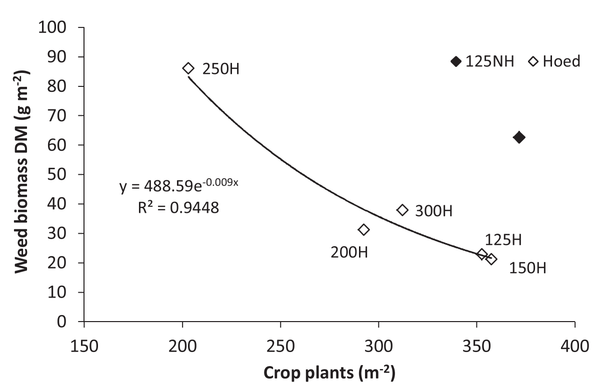

Fig. 3. The relationship between total weed biomass and crop plant density of spring wheat in 2015. Observed values are means for 125NH and 125H–300H but across the two N levels (50N and 100N).

or treatments 125H–300H (data not shown). The biomass of spring barley was 46% greater with 100N than with 50N in 2015 ($P < 0.0001$). The biomass of spring wheat also responded to N input in 2015 where 100N increased biomass production by 19% ($P = 0.0529$) as compared to 50N (data not shown). Increasing the N level in 2016 increased the crop biomass of spring barley and wheat by 16% and 10% respectively ($P = 0.0088$ and $P = 0.0519$ respectively). Treatments 125H–300H only had a minor influence on crop biomass in 2016.

3.4. Grain yield

3.4.1. Stage (I) analysis

Spring barley yielded in general 18% more grain than spring wheat ($P = 0.0006$). Higher N input increased yield by 18% in barley ($P = 0.0004$) and 20% in wheat ($P = 0.0005$) and did not interact with inter-row spacing. The main effects of treatments 125NH – 300H are shown for both crops in Table 4. It is noteworthy that 200H and 250H had the lowest yields in both crops while 300H was either equal (wheat) to 125NH and 125H or slightly lower (barley) than standard inter-row spacing.

3.4.2. Stage (II) analysis

The analyses of yield data were undertaken year and crop-wise due to strong 3-way and 4-way interactions. Barley grain yield was not affected by N level in 2014. Significant differences in yields were only caused by inter-row hoeing ($P < 0.0001$). 200H and 300H resulted in the lowest yields at both N levels (Table 5). These two treatments also had the smallest crop stands (Table S2), which largely explained the yield differences assuming that the low weed level in 2014 only had a minor impact on crop yield.

In 2015, barley grain yield was affected by both N input and inter-row hoeing ($P = 0.0011$ and $P < 0.0001$, respectively). The two factors did not interact significantly and 200H and partly 250H resulted in the lowest yields (Table 5). A plausible reason for these lower yields is that the hoe shares caused substantial soil coverage of the crop leaves. Differences in crop stands were minor and the low weed pressure in 2015 (Fig. 1) probably did not interfere with crop growth. Obviously, the low crop plant density for 250H in spring wheat in 2015 resulted in a significantly lower yield for 250H and 50N because the weeds competed more strongly with the crop (Fig. 3).

100N produced a 16% higher yield in barley in 2016 compared with 50N ($P = 0.0061$) and N input did not interact with inter-row spacing. Again, 200H and this time also 150H at 50N caused lower yields at both N levels. This was not attributed to a reduction in crop stand (Table S2) but seemed to relate to crop injuries from hoeing. The stage (II) analysis did not reveal any differences between inter-row spacing in wheat in 2016. However, a regression analysis with weed biomass as the covariate and N level as the categorical variable showed a linear relationship between wheat yield and weed biomass with a common slope for both N levels ($P = 0.0230$): 6.3 kg ha^{-1} g^{-1} m^2 (Fig. 4). 100N increased wheat yield by 33% in 2016 in comparison with 50N ($P < 0.0001$).

Table 5
Stage (II) analyses showing least square means (LSMs) of grain yields, protein contents and thousand kernel weights (TKW) for each year, crop, nitrogen level and inter-row spacing. Different letters alongside LSMs in rows within year, crop and nitrogen level indicate significant differences at $P \le 0.05$ (Tukey–Kramer test). SED is maximum standard errors of differences between means.

Year	Crop	NH_4-N kg ha^{-1}	Inter-row spacing (mm)						SED
			125NH	125H	150H	200H	250H	300H	
			Grain yield (t ha^{-1})						
2014	Barley	50	4.35^{a}	4.38^{a}	3.98^{ab}	3.37^{b}	3.95^{ab}	3.85^{ab}	*0.210*
		100	4.73^{a}	4.19^{ab}	4.12^{ab}	3.84^{b}	4.30^{ab}	3.74^{b}	*0.229*
2015	Barley	50	5.48^{a}	5.51^{a}	5.11^{ab}	4.24^{b}	4.64^{ab}	5.75^{a}	*0.307*
		100	7.46^{a}	6.93^{ab}	6.72^{ab}	6.32^{b}	6.61^{ab}	6.75^{ab}	*0.282*
	Wheat	50	5.49^{ab}	5.93^{a}	5.22^{ab}	5.26^{ab}	4.35^{b}	5.04^{ab}	*0.400*
		100	5.98^{a}	6.45^{a}	6.31^{a}	5.59^{a}	5.56^{a}	5.68^{a}	*0.347*
2016	Barley	50	4.62^{a}	4.23^{a}	3.48^{b}	3.58^{b}	4.29^{a}	4.02^{a}	*0.280*
		100	5.33^{a}	5.17^{a}	4.60^{ab}	3.95^{b}	4.60^{ab}	4.49^{ab}	*0.255*
	Wheat	50	3.18^{a}	2.69^{a}	2.79^{a}	2.58^{a}	2.69^{a}	3.17^{a}	*0.294*
		100	3.75^{a}	3.88^{a}	3.95^{a}	3.27^{a}	3.51^{a}	4.17^{a}	*0.294*
			Protein content (%)						
2014	Barley	50	12.4^{a}	13.4^{ab}	13.2^{ab}	13.7^{b}	12.9^{ab}	13.6^{b}	*0.34*
		100	14.3^{a}	14.0^{a}	14.0^{a}	14.0^{a}	13.7^{a}	14.0^{a}	*0.37*
2015	Barley	50	7.1^{a}	6.9^{a}	7.1^{a}	7.6^{a}	7.5^{a}	7.2^{a}	*0.47*
		100	7.8^{a}	7.6^{a}	8.0^{ab}	8.1^{ab}	8.3^{ab}	9.2^{b}	*0.39*
	Wheat	50	8.6^{a}	9.3^{a}	8.6^{a}	9.1^{a}	9.1^{a}	8.8^{a}	*0.33*
		100	9.1^{a}	9.4^{a}	9.6^{a}	9.5^{a}	9.7^{a}	9.6^{a}	*0.28*
2016	Barley	50	10.1^{a}	10.2^{a}	10.2^{a}	9.9^{a}	10.2^{a}	9.9^{a}	*0.24*
		100	11.0^{a}	11.2^{a}	11.1^{a}	11.3^{a}	11.2^{a}	11.2^{a}	*0.22*
	Wheat	50	12.5^{a}	13.2^{a}	12.7^{a}	12.9^{a}	13.4^{a}	13.1^{a}	*0.29*
		100	13.7^{a}	13.9^{a}	13.9^{a}	14.0^{a}	14.5^{a}	14.1^{a}	*0.29*
			TKW (g)						
2014	Barley	50	45.2^{a}	47.1^{a}	46.3^{a}	47.1^{a}	48.1^{a}	47.3^{a}	*1.15*
		100	44.9^{a}	45.8^{a}	46.3^{a}	48.7^{a}	47.6^{a}	45.8^{a}	*1.24*
2015	Barley	50	42.6^{a}	42.2^{a}	42.4^{a}	42.3^{a}	43.0^{a}	43.7^{a}	*1.20*
		100	43.7^{a}	45.9^{a}	44.5^{a}	45.7^{a}	46.7^{a}	44.2^{a}	*1.10*
	Wheat	50	48.5^{a}	49.9^{a}	48.2^{a}	50.4^{a}	50.7^{b}	48.2^{a}	*0.76*
		100	49.2^{a}	49.9^{a}	50.2^{a}	50.9^{a}	50.6^{a}	49.5^{a}	*0.66*
2016	Barley	50	49.4^{a}	48.5^{a}	47.9^{a}	48.9^{a}	49.0^{a}	50.0^{a}	*0.89*
		100	49.3^{a}	48.2^{a}	48.9^{a}	48.1^{a}	50.3^{a}	49.3^{a}	*0.81*
	Wheat	50	43.3^{ab}	40.6^{a}	43.0^{ab}	43.5^{ab}	42.5^{ab}	44.5^{b}	*0.99*
		100	44.1^{a}	43.1^{a}	42.3^{a}	43.7^{a}	43.3^{a}	44.6^{a}	*0.99*

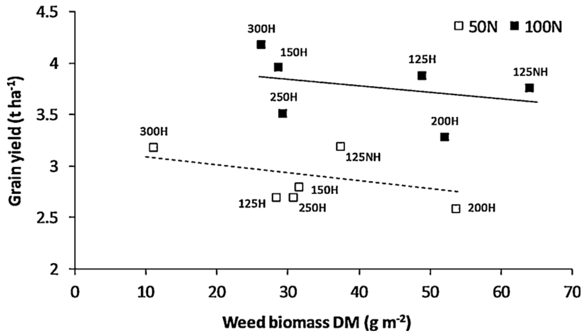

Fig. 4. Linear relationships between total weed biomass and grain yield of spring wheat in 2016. Observed values are means for 125NH and 125H–300H for both N levels (50N and 100N).

3.5. Grain quality

3.5.1. Stage (I) analysis

In neither crop did N level interact with inter-row spacing on TKW and only in wheat did 100N increase TKW by 2% ($P = 0.0164$). Table 4 shows the main effects for treatments 125NH–300H on TKW in both crops, though with only minor differences between the inter-row spacings. The protein content of barley grain increased by 9% with 100N ($P < 0.0001$) but with no differences between treatments 125NH–300H (Table 4). Protein content of wheat grain was also raised by 6% in general with 100N ($P = 0.0038$) and tilling the soil in general improved protein content by 4% when contrasting 125NH with 125H–300H ($P < 0.0001$).

3.5.2. Stage (II) analysis

Inter-row hoeing did not reduce the grain quality of barley or wheat in terms of protein content and TKW in any year (Table 5), assuming that high TKW and protein content are desirable.

4. Discussion

4.1. Weed control

Inter-row hoeing at increasing inter-row spacings did not consistently provide greater weed control. Only for the immediate effects for treatment 300H and for total weed biomass in 300H in spring wheat in 2016 could the hypothesis that 'increasing the inter-row space results in greater weed control from inter-row hoeing' be supported. The immediate effects on weed numbers are expected to increase when a larger area is tilled. However, the intra-row competition exerted by the crop rows probably caused considerable mortality among weed seedlings between the two weed counts (before and shortly after treatment), which might have blurred differences in the tilled area. The higher weed control effect at 300H in wheat in 2016, both in terms of weed number and biomass, was probably promoted by dry weather in the first weeks after treatment (Melander et al., 2003). Weed seedlings were better controlled and regrowth of weeds less pronounced in 300H compared to 125H–250H. If weed pressure were high and rainy weather prevailed, inter-row weed growth would be more vigorous, since a wide inter-row spacing would allow more light to penetrate to the bottom of the canopy in the inter-row space. Such a situation requires multiple hoeing passes for satisfactory control. When inter-row hoeing significantly reduced total weed biomasses, the effects were close to those (60–70%) reported for inter-row hoeing in spring in winter wheat (Melander et al., 2003).

The proportion of the inter-row area directly impacted by the share widths was not exactly the same for all inter-row spacings (see Table 1). This could imply that effects of share width and inter-row spacing were confounded. However, hoeing shares fraction the soil beyond their share width and the goosefoot type share used here creates considerable sideward soil movement as well (Znova et al., 2018); both factors causing significant mortality among small sized weed plants. So differences in 'untreated' areas are believed to have had minor, if any, importance in this study, though detailed studies are required for full clarification.

4.2. Nitrogen input

The manure N rate 100N did not lower weed biomass in the two crops, but remained similar to 50N, irrespective of inter-row spacing and hoeing. However, both barley and wheat benefited from 100N in 2015 and 2016 and produced more biomass in comparison with 50N. The total biomass production (weeds plus crop) was thus enhanced by a rise in N availability and the proportion of crop biomass relative to weed biomass increased. Hence, the hypothesis suggesting that 'increasing the nitrogen input improves crop growth relative to weed growth' is supported. In a long-term organic cropping experiment at three sites in Denmark, Olesen et al. (2007) found no effect of manure application in spring barley on the proportion of annual weeds in biomass, whereas annual weed proportion increased in winter cereals with manure application (Olesen et al., 2009). For perennial weeds, Melander et al. (2016) observed no general effect of N fertilisation in manure on weed biomass in organic cropping systems. However, *Elytrigia repens* (L.) Nevski in particular deviated from the overall picture by increasing its growth following the application of manure, but not to the same extent as the crops (Melander et al., 2016). Meanwhile Rasmussen et al. (2014) improved the suppression of *E. repens* by increasing N input on coarse sand that had low fertility. Other contrasting results with organic amendments on weed growth have been reported (Melander et al., 2017).

4.3. Crop competiveness

Spring wheat had more weed growth than spring barley, despite initial weed pressures being approximately the same in the two crops (Table 2). The immediate weed control effects were greater in barley, and markedly less weed biomass remained after inter-row hoeing due to barleys better suppression of surviving weeds. This confirms the hypothesis that 'weed control effects are greater in spring barley than in spring wheat'. In general, growth of spring barley was vigorous in all years and substantially suppressed weed growth. Judged on the small amount of weed biomass in 125NH, there was no real need for inter-row hoeing in barley. The competitive ability of spring wheat is less than for barley, particularly in terms of its more limited ability to tiller and its slower initial growth rate (Peltonen-Saino et al., 2008).

4.4. Grain yield and quality

Only in spring wheat in 2016 did the weed control provided by inter-row hoeing increase crop yield, otherwise the yields were similar to or lower than 125NH. A number of factors are involved in the crop yield responses to hoeing and inter-row spacing, but essentially yields are the sum of both negative and positive effects that work simultaneously and cannot be separated in the present type of experimental design. Positive effects associated with hoeing include the reduction of weed competition that occurs when weeds are removed, increased mineralisation and thus N mobilisation from improved aeration of the soil, increased water availability and improved root growth (Thomsen et al., 2008). Negative effects encompass crop injuries from hoe shares impacting the crop due to inaccurate steering or hoeing too close to the crop plants, and a general yield decline combined with widening the inter-row spacing (Melander et al., 2003). Early loss of crop plants and presumably excessive soil coverage of crop plants from hoeing (Melander et al., 2017) were the two main causes of the yield reductions seen in this study. Fewer productive tillers were produced and reductions in the number of kernels per ear (not recorded here) probably also played a role (Carr et al., 2003) since TKW was not reduced by widening inter-row spacing. It was particularly evident in spring wheat in 2015 that crop density needs to be maintained when widening inter-row spacing to preserve crop competitiveness and yield (Fig. 3 and Table 5).

In general, there was no evidence to confirm that widening of the inter-row spacing to allow for a larger proportion of the surface area to be tilled reduces yields or grain quality. In fact, inter-row spacing 150H–300H performed equally well to 125NH, provided that crop injuries were absent and crop densities were equal or close to those of 125H. Assuming that the positive and negative effects mentioned above only had a minor influence on yield, there is not much evidence to suggest that widening of inter-row spacing will be accompanied by a yield penalty or lower grain quality. Thus the hypothesis that 'crop yields and grain quality are unaffected by inter-row spacing and hoeing' can be supported. This is in line with Hiltbrunner et al. (2005) and Kolb et al. (2012), but in contrast to investigations undertaken on both spring and winter cereals under conventional growing conditions using mineral fertilisers (*e.g.* Johansson, 1998; Melander et al., 2003; Rasmussen and Pedersen, 1990). Under conventional farming conditions, yield reductions typically occur for inter-row spacing beyond 200 mm. The majority of these studies agree that these yield reductions are most pronounced at high yield levels, which are not typical for organic growing conditions that use manures from which nutrients are released more slowly and are less abundant (Melander et al., 2005).

4.5. Implications for weed management

Inter-row hoeing has no relevance for weed control in organic spring cereals when weed pressures are low to moderate and tall-growing, competitive weed species are absent or only occur in small numbers. Weeds are sufficiently well managed by the suppression exerted by the crop if soils are fertile and promote vigorously crop growth (Melander et al., 2016). However, weed pressures can be severe in organic cropping systems, and in such cases inter-row hoeing offers a feasible solution (Kolb et al., 2010, 2012). The 300-mm wide inter-row spacing is particularly interesting since it allows a greater proportion of weeds to be directly impacted by the hoe shares. It only partly controlled more weeds in this study, but the effect can be expected to be more pronounced when problematic weed species are more abundant. In addition, more shoots of perennial weeds are controlled with 300 mm inter-row spacing than with a narrower spacing, and repeated treatments may hamper perennial weed growth significantly (Melander et al., 2012). Wide rows also offer good conditions for the under-sowing of cover crops after the last inter-row cultivation with the purpose of post-harvest weed suppression and nutrient uptake (Bertelsen, 2017). More light penetrates into the inter-row space to assist cover crop establishment and subsequent growth with wide rows (Kolb et al., 2012) than with the standard spacing of 125 mm.

Finally, the results presented here would need further evaluation before general recommendations can be made. Driving speeds were low in this study, not reflecting those relevant for practise, and therefore the performance of inter-row hoeing need to be tested under conditions that are more realistic for practical farming.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2018.08.005.

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